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Implementation Options for the PROPEL Electrodynamic Tether Demonstration Mission

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***Abstract*—The PROPEL flight mission concept will demonstrate the safe use of an electrodynamic tether for generating thrust. PROPEL is being designed to be a versatile electrodynamic-tether system for multiple end users and to be flexible with respect to platform. As such, several implementation options are being explored, including a comprehensive mission design for PROPEL with a mission duration of six months; a space demonstration mission concept design with configuration of a pair of tethered satellites, one of which is the Japanese H-II Transfer Vehicle; and an ESPA-based system. We report here on these possible implementation options for PROPEL.**

Keywords—electrodynamic tether; PROPEL demonstration mission; propellantless propulsion

I. Introduction

The PROPEL ("Propulsion using Electrodynamics") flight demonstration mission concept is designed to demonstrate the safe operation of an electrodynamic tether (EDT) for generating thrust, which will allow the propulsion system to overcome the limitations of the rocket equation. The mission concept has been developed by a team of government, industry, and academia partners led by NASA Marshall Space Flight Center (MSFC). PROPEL has been designed for versatility of the EDT system with multiple end users in mind and to be flexible with respect to platform.

PROPEL has two primary goals: (1) to demonstrate capability of EDT technology to provide robust and safe, near-propellantless propulsion for orbit-raising, de-orbit, plane change, and station keeping, as well as to perform orbital power harvesting and formation flight; and (2) to fully characterize and validate the performance of an integrated EDT propulsion system, qualifying it for infusion into future multiple satellite platforms and missions with minimum modification.

We reported previously on a comprehensive mission design for PROPEL with a mission duration of six months or longer [refs TBD]. To explore a range of possible implementation configurations, driven primarily by cost and launch vehicle considerations, other mission concept designs are being pursued such that a reduced system can be demonstrated should a flight opportunity be identified.

In this paper, we report on several possible implementation options for PROPEL. Section II reviews the PROPEL Design Reference Mission. We then discuss several implementation options, which include the HTV (Section III), the ALTAIR (Section IV), and a Small-Sat Servicing Platform that uses a free-flying ESPA ring (Section V). Section VI concludes the paper.

II. PROPEL Design Reference Mission

The material provided below is a summary of previously reported material. More details may be found in refs TBD.

PROPEL is intended to significantly advance the technology readiness level (TRL) of an EDT propulsion system that can safely support a broad range of capabilities, including boost, deboost, inclination change, drag make-up, and energy harvesting. In contrast to a system with more focused goals, e.g., providing only deorbit or drag make-up, PROPEL's mission goals require a system architecture that has an appropriate level of symmetry to enable tether current flow in both directions (boost and deboost). To this end, the PROPEL design team defined a set of mission objectives, detailed in Table 1, to establish EDT propulsion ready for operational use.

Figure 1 illustrates the PROPEL system architecture. The PROPEL space vehicle consists of the Host Side (HS) spacecraft and Endmass (EM) spacecraft separated by a 3-km tether with the HS at the lower altitude. The EDT propulsion hardware consists of a 3-km conducting, multi-string tether with a tether deployer on each end body. The tether is fabricated with a Hoytether™ structural design to provide high probability of survival for the mission duration in the LEO micrometeoroid and orbital debris (MM/OD) environment [Hoyt TBD]. The reel-type deployer has deployment and retrieval operational flight heritage with the two Tethered Satellite System (TSS) missions. A Hollow Cathode Plasma Contactor (HCPC) on the host and end mass is used for electrical contact with the ionosphere.

PROPEL tether deployment will be monitored by on-board cameras, accelerometers, and tensiometers. The tether and deployment system also includes cutters and dual retractors on each side to enhance system safety in the event of a severed

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tether. The tether diagnostic hardware will provide tether dynamics, electrodynamic performance, and natural ionospheric and PROPEL-induced plasma environments measurements. Measurement correlations will validate existing theoretical models and allow us to extrapolate performance to a broad range of space conditions and applications. The Langmuir probe provides reliable electron data at the boom tip. The hemispherical RPA offers a wide angle integrated ion flux measurement. To determine ion energy and density requires angle-of-incidence information provided by the Deflection Plate Analyzer (DPA).

Table 1. PROPEL will demonstrate capabilities that will enable new missions [ref TBD].

PROPEL Objective	Capability Enabled
System-level demonstration of safe ED tether propulsion delivering high thrust-to-power and large total impulse for LEO maneuvering and station keeping	• Low-mass systems to produce large ΔV, reducing launch vehicle size and total life-cycle costs for many future missions • Highly efficient orbital maneuvering and plane change of LEO spacecraft • Long-duration, low-LEO drag makeup of large space systems
Accurately predict, verify, and safely control ED tether orbital maneuvering, and validate simulation and modeling tools	• Multiple precise orbital maneuvers and rendezvous with small, affordable systems • Long duration precision station keeping • Predictive control ensures flight safety
Demonstrate orbital energy harvesting	• High burst power with lower mass and cost • Power generation at the outer planets without RTGs
Validate survival and operation of a conducting tether for an extended period	• Tether performance data over a long mission duration will enable extrapolation to extended periods

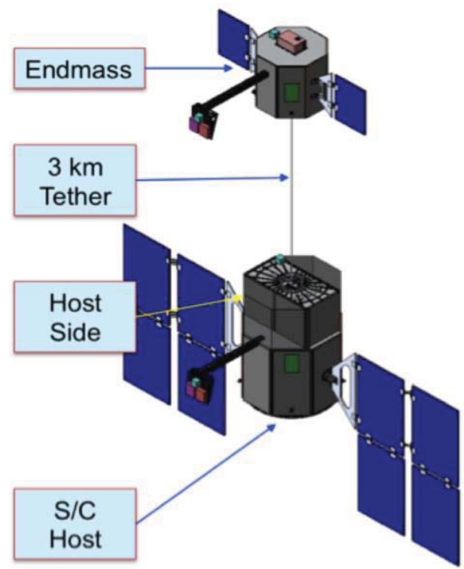

Fig. 1. The PROPEL consists of two spacecraft connected by a 3-km conducting tether [ref TBD].

In addition to a proposed system architecture described above, we established a Design Reference Mission (DRM) for PROPEL to demonstrate the necessary EDT operational readiness objectives during its six-month mission life (see Fig. 2). PROPEL's multi-step demonstration approach provides operational capability data in a characterized plasma environment to validate operational EDT propulsive systems immediately after commissioning.

For the DRM, PROPEL launches into a 500-km circular orbit. This altitude provides very good environmental plasma conditions for the demonstration (e.g. ionospheric plasma electrical conductivity). A 500-km insertion also allows for a complete system checkout and tether deployment at an altitude above the International Space Station (ISS) orbit, and provides for a slow passive decay in case of an operational anomaly. Tether deployment will be initiated after solar array deployment, host spacecraft (HS) and end mass (EM)

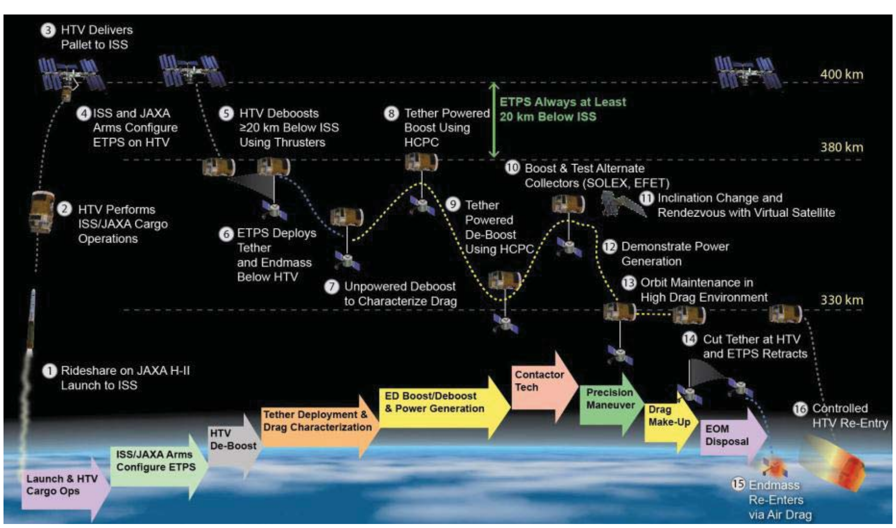

Fig. 2. The PROPEL concept of operations (CONOPS) will demonstrate orbit-raising, orbit-lowering, and inclination change with an EDT.

checkout, instrument boom deployment, and HS/EM separation.

PROPEL will demonstrate full ED tether propulsive capabilities by raising the orbit from 500 km to 650 km after tether deployment and initial characterization. Diagnostic instruments are mounted on each end-body and allow the propulsive performance to be correlated with the surrounding space plasma environment. Following validation, the existing analytic performance models will be used to predict ED tether performance to support mission operations. Subsequent mission phases include deboost/power generation, inclination change, precision orbital maneuvering, drag make-up, and deorbit.

III. PROPEL HTV Implementation

A. Electrodynamic Tether Propulsion Study

With support from NASA's Space Technology Mission Directorate and the NASA MSFC Advanced Concepts Office, a mission concept design was developed for a near-term EDT propulsion flight validation mission. The Electrodynamic Tether Propulsion System (ETPS) study defined an EDT propulsion system implementation capable of very large delta-V for use on future missions developed by NASA, DoD, and commercial customers.

To demonstrate the feasibility of an ETPS, the study focused on a space demonstration mission concept design with configuration of a pair of tethered satellite busses, one of which is the Japanese H-II Transfer Vehicle (HTV). The HTV would fly its standard ISS resupply mission. When resupply mission is complete, the ISS reconfigures and releases the HTV to perform the EDT experiment at safe orbital altitudes below the ISS. Though the focus of this particular mission concept design addresses a scenario involving the HTV or a similar vehicle, the propulsion system's capability is relevant to a number of applications, as noted above. The spacecraft is designed for minimal impact to HTV systems and will occupy only a portion of the HTV's payload accommodation (see Fig. 3). The ETPS builds on prior work on long-life, failure-resistant, conducting tethers and includes an instrument suite with demonstrated heritage capable of performing necessary diagnostics to measure performance against predictions for a given system size (to be determined) and boost rate.

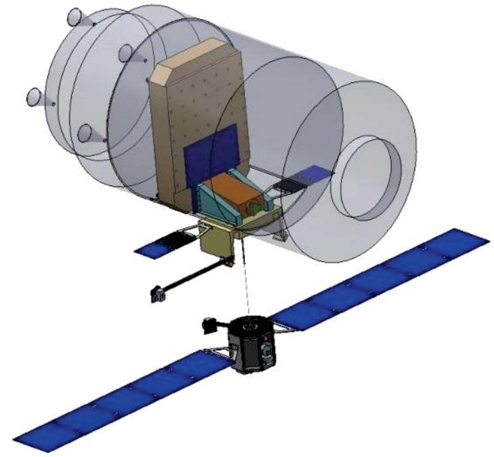

Fig. 3. Design concept for PROPEL on the HTV [ref TBD].

Since the HTV is substantially more massive than the free-flyer PROPEL concept detailed in Section II above, the system's power requirement was increased from 1 kW to 2 kW. This precipitated a slight increase in tether size and solar-array power capability. In this mission concept, upon completing its primary mission objectives and departing from ISS, the HTV proceeds to a distance designated to be outside of the ISS operational volume, at which point the tether system will be deployed below the HTV. While tethered to the HTV, an in-space demonstration of a fully operational ETPS will be executed to boost and deboost the system mass and demonstrate energy harvesting. The tether spacecraft will carry out a series of controlled spacecraft propulsion maneuvers with critical performance measurements taken by onboard diagnostic instrumentation to verify predicted performance. Upon accomplishing its mission, the ETPS will have demonstrated the steps necessary to advance the system level TRL to 7–8.

Fail-safe features are integrated into the system design. Tether retrieval is accomplished from the EM. The EM is deployed below the HTV. In the event of a catastrophic break in the tether, the EM would have downward acceleration in a high drag region where it would re-enter rapidly and burn up. Momentum would be conserved, posing no risk and minimal movement for the HTV. The HTV also has its own propulsion system and can drive itself to a nominal reentry, if needed.

The baseline concept design will include: mission and operation definition; identification and appropriate sizing of all components to be determined by analysis; baseline list of critical measurements to quantify performance; characterization of key technology risk; spacecraft bus design and system and integration requirements definition; and system safety impacts for manned systems. Given the proximity to other space assets, the demonstration mission concept is operationally very safe for ISS. The ISS community has provided data to determine sufficient altitude and clearance down and away from ISS for the ETPS demonstration.

IV. ALTAIR PROPEL Implementation

Another implementation option is using the ALTAIR satellite bus platform described below. Launch could occur

from a number of possible vehicles and/or using the ESPA ring.

A. Generic ALTAIR Spacecraft Overview

Millennium Space Systems designed and developed the ALTAIR "27U" (where 1U represents a standard 10×10×10-cm CubeSat form factor) satellite bus platform under DARPA's SeeMe (Space Enabled Effects for Military Engagements) program. ALTAIR represents a game-changing spacecraft class addressing military, civil, and commercial needs, balancing extreme affordability, performance, and schedule responsiveness. DARPA's overarching SeeMe requirement called for a spacecraft constellation with satellites flying in any orbit at less than US$500K cost each and readiness to launch 90 days after call-up. To achieve both high performance and low cost, Millennium adopted key development processes and instituted nontraditional spacecraft and subsystem designs.

The 27U spacecraft configuration is manufactured using modern additive processing for rapid prototyping, flexible design, low-cost, non-continuous production based on mission requirements, provided payload's configuration, and parts availability. The ALTAIR satellite flight-control system features a low-cost, high-performance attitude sensor suite with actuators and advanced estimation-and-control algorithms to achieve high-level pointing accuracy generally associated with mainline imaging missions. Existing tactical-compatible radios serve as uplink, downlink, and crosslink to reduce cost, minimize complexity, and enhance communications as a cost-effective solution to achieve high data rates and effectively replace traditional ground station control systems. Flight software is coded directly from simulation models developed in a fast-prototype fashion. The spacecraft is constructed from commercial-off-the-shelf (COTS) components to reduce cost and shorten production schedules.

ALTAIR, based on the SeeMe requirements, is a highly compact, modular, scalable, and reconfigurable spacecraft with agility and processing power to support demanding missions, while providing ultra-low cost mission solutions. ALTAIR is a revolutionary product to serve the increasing demands of multiple users, multiple missions, multiple theaters, and multiple CONOPS—on tightly constrained budgets and on operationally relevant timelines.

B. PROPEL ALTAIR Implementation

The ALTAIR spacecraft can host a payload between 25–80 kg either in its relatively spacious internal envelope or externally to the bus. The payload accommodations could support a simple short-lived PROPEL EDT demonstration in which all necessary components could fit inside the existing spacecraft design. Using two ALTAIR spacecraft connected by a Planetary Systems Corporation Lightband separation system, a 1-to-3-km tether deployer and associated electronics may be hosted on one spacecraft. A High Voltage Power Supply (HVPS), HCPC, and system control electronics could be hosted on the second spacecraft. This system would provide a boost or deboost demonstration at very low cost. See Fig. 4 for a diagram of this implementation.

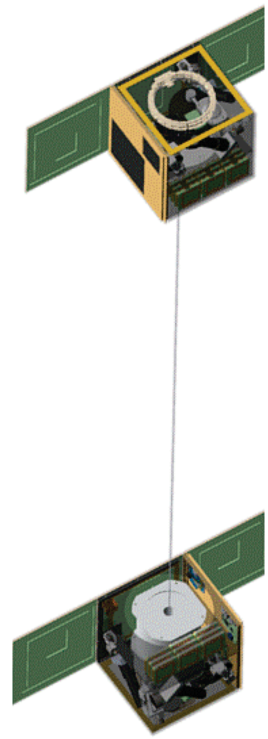

Fig. 4. Millennium's ALTAIR bus developed for DARPA's SeeMe Program offers a low-cost EDT test mission option.

The experiment could arrive in a Low Earth Orbit (LEO) using either one slot on an EELV Secondary Payload Adapter (ESPA) ring or other secondary launcher payload opportunity available. Upon launch vehicle separation, the satellite drifts naturally from the launch vehicle. Prior to tether deployment, the designated "Host" ALTAIR satellite begins Earth-pointing attitude control. When conditions are safe and ground communications coverage adequate, the combined spacecraft would be commanded to separate and deploy the tether. The designated ALTAIR satellite EM is ejected at an initial velocity of approximately 2 m/s. After deployment reaches about 500 meters, gravity-gradient forces dominate and the deployment is braked. PROPEL Flight Experiment satellite solar panels are deployed, systems activated, and deployment continues using the End Mass Deployment Assist Mechanism inside the Tether Deployer at a slow rate and again when good ground communications are available. When the tether is fully deployed all PROPEL EDT systems are fully checked out and prepared for operations.

The main purpose of the PROPEL Flight Experiment is to validate EDTs as a means to provide virtually unlimited propulsion in Low Earth Orbit. The PROPEL Flight Experiment is also meant to validate tether dynamics and performance models. Initially, basic boost delta-V operations to specifically change various orbital elements will be implemented to fully test the EDT systems. Next, various demonstration scenarios will be implemented to flush out tether dynamics and performance models ability to predict actual powered flight results. Various test sequences will be implemented over different periods with on-orbit tether operations lasting as long as possible. When EDT flight experiments are complete, the system will naturally deorbit and burn up in the atmosphere.

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V. ESPA-BASED PROPEL CONCEPT

Another tether demonstration concept considered is similar to the ALTAIR two-spacecraft approach, but uses a free-flying ESPA ring in place of one of the ALTAIR spacecraft. An ESPA (EELV Secondary Payload Adapter) is a low-cost aluminum structure with a mass of roughly 125 kg that uses the excess lift capacity of an Evolved Expendable Launch Vehicle (EELV, e.g., Falcon 9, Delta 4, Atlas 5) to launch small secondary spacecraft (typically six per ring, with mass less than 180 kg each). For our demonstration, one of these secondary spacecraft would be an ALTAIR spacecraft that is tethered to one of the ESPA's deployment ports. For launch, the ESPA with its secondary spacecraft is installed between the rocket and its larger primary spacecraft using standard separation mechanisms (see Fig. 5). ESPA rings may either remain attached to the rocket for short duration experiments (up to one week with extra EELV battery option) or released from the rocket to conduct free-flying missions after rocket disposal (several months duration, which provides more data return but at higher cost due to longer operation).

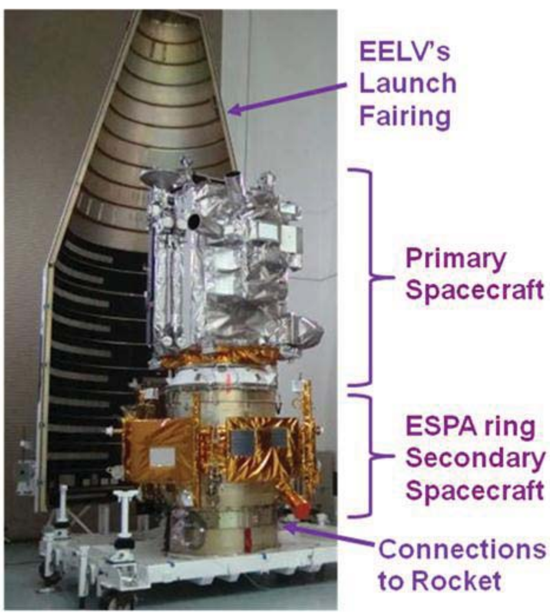

Fig. 5. ESPA ring stacked for launch.

In our concept, the EELV is launched into Low Earth Orbit at an inclination and altitude set by the primary spacecraft's mission. Once the primary spacecraft is released from the EELV, the EELV performs a collision avoidance burn to place the ESPA into the desired initial altitude orbit for conducting the tether demonstration. The ESPA orients its solar arrays to the sun and deploys the tether with the ALTAIR spacecraft as its end mass, then begins converting sunlight into electromagnetic thrust using the tether (see Fig. 6). Once deployed, the ESPA–ALTAIR tether system can perform demonstration maneuvers similar to those described in Section IV, albeit with more mass due to the ESPA.

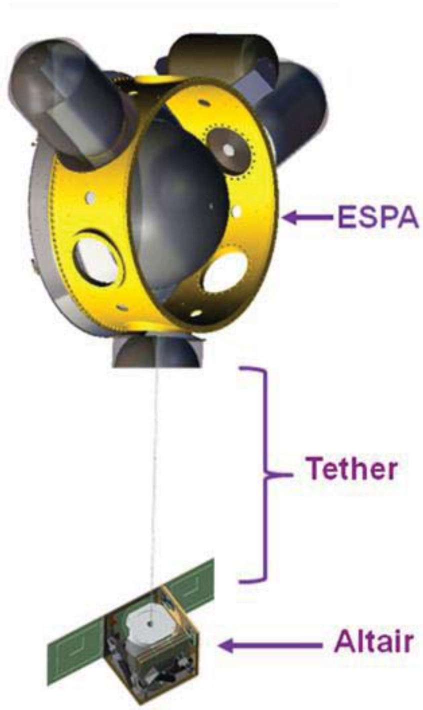

Fig. 6. ESPA-based tether system in deployed state.

This ESPA-based tether demonstration concept has the advantage of sharing the cost of the launch with the primary spacecraft, which could result in significant savings. The disadvantage is that the altitude and inclination are limited by the primary spacecraft's mission launch parameters. This concept would require further development and tether authorization in order to implement, but is feasible with low risk and could serve as the basis for useful operational tether missions such as a small satellite re-boost and servicing platform.

VI. CONCLUSIONS

The PROPEL mission represents a significant effort to advance the TRL of EDT technology to an operational level by demonstrating the EDTs are viable and can be operated safely. The PROPEL EDT system is being configured to validate operations associated with boost, deboost, inclination change, drag make-up, energy harvesting, and deorbit. We have developed several implementation options for EDT demonstration missions. . These options demonstrated that PROPEL is a versatile EDT system for multiple end users and is flexible with respect to platform.

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